

Radio scintillation of gamma-ray-burst afterglows [★]

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Abstract

Stars twinkle to the eye through atmospheric turbulence, but planets, because of their larger angular size, do not. Similarly, scintillation due to the local interstellar medium will modulate the radio flux of gamma-ray-burst afterglows and may permit indirect measurements of their angular sizes. The amplitude of refractive scintillation is of order ten percent at ten gigahertz unless the source size is much larger than the expected size, of order ten microarcseconds. Diffractive scintillation is marginally possible, depending sensitively on the source size, observing frequency, and scattering measure of the interstellar medium.

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1 INTRODUCTION

At the time of writing, three gamma-ray bursts discovered by the BeppoSAX satellite have been associated with transient sources at longer wavelengths ([Costa et al. 1997], [Feroci et al. 1997], [Piro et al. 1997], [Costa et al. 1997], [Bond 1997]). Absorption lines of iron and magnesium at $z = 0.835$ in the optical counterpart of GRB0508 appear to prove that this burst, at least, lies at a cosmological distance ([Metzger et al. 1997]). GRB0508 is also the first burst associated with a radio transient ([Frail & Kulkarni 1997], [Pooley & Green 1997]).

These X-ray-to-radio “afterglows” are broadly consistent with models based on relativistic blastwaves at cosmological distances ([Rees & Mészáros 1992], [Paczynski & Rhoads 1993], [Waxman 1997], [Wijers et al. 1997], and references therein). In these models, the shock Lorentz factor is $\gtrsim 300$ at the time of the gamma-ray event and falls thereafter as $\Gamma_s \propto t^{-3/8}$, t being the time measured at Earth. The bulk Lorentz factor of the postshock material is $\Gamma_{\text{ps}} = 2^{-1/2}\Gamma_s$. For synchrotron emission, the flux density F_ν at frequency ν is predicted to peak at a time $t_\nu \propto \nu^{-3/2}$ if the source is optically thick ([Paczynski & Rhoads 1993]), or $t_\nu \propto \nu^{-2/3}$ if optically thin (cf. [Waxman 1997], [Wijers et al. 1997]).

A lower limit to the angular size $\theta_s = r_s/D$ of the radio source follows if the brightness temperature is not larger than the Compton limit for incoherent synchrotron radiation, $T_b \lesssim \Gamma_{\text{ps}}(1 + \beta_{\text{ps}})T_{\text{max}}$ with $T_{\text{max}} \approx 10^{12}$ K ([Kellermann & Pauliny-Toth 1969]):

$$\theta_s \geq 1.5 \left[\frac{1+z}{(1+\beta_{\text{ps}})\Gamma_{\text{ps}}} \right]^{1/2} \left(\frac{F_\nu}{\text{mJy}} \right)^{1/2} \nu_{10}^{-1/2} \left(\frac{T_{\text{max}}}{10^{12} \text{K}} \right)^{-1/2} \mu \text{ a.s.}, \quad (1)$$

where $\nu_{10} \equiv \nu/(10 \text{ GHz})$. [Sari (1997)] has pointed out that the radius of the shock at observed time t is $R_s = 8\Gamma_s^2 ct$ for $\Gamma_s \gg 1$ since $\Gamma_s \propto t^{-3/8}$. Most of the emission is seen from a disk of radius R_s/Γ_{ps} , so

$$\theta_s = \frac{ct}{d} \times \begin{cases} 8\sqrt{2}\Gamma_s & \Gamma_s \gg 1; \\ (5/2)\beta_s & \beta_s \equiv (1 - \Gamma_s^{-2})^{1/2} \ll 1 \end{cases} \quad (2)$$

where d , the proper motion distance of the source, is $(1+z)$ times the angular-size distance (cf. [Weinberg 1972]), and the nonrelativistic formula above follows from the Sedov solution. Comparison of relations (1) and (2) yields lower bounds on Γ_s as well as θ_s . Thus for example, the radio counterpart of GRB0508 had a flux density of 0.61 ± 0.04 mJy at 8.46 GHz 6.2 days after the burst ([Frail & Kulkarni 1997]). Using a smooth interpolation between the ultrarelativistic and nonrelativistic formulae above, and for the relation

between Γ_s and Γ_{ps} , we find $\beta_s \gtrsim 0.5$ and $\theta_s \gtrsim 1.5 \mu \text{ a.s.}$ at the time of this observation, assuming $z = 1$ and $d = 10^{28} \text{ cm}$ (3 Gpc). The spherical blastwave models cited above predict somewhat larger values, depending on parameters. For example, [Sari (1997)]’s estimates imply $\Gamma_s \approx 2.6(E_{52}/n_1)^{1/8}$ at $t = 6.2 \text{ d}$, where E_{52} is the energy of the blastwave in units of 10^{52} erg and n_1 is the density of the external medium in cm^{-3} ; this implies $\theta_s \approx 9 \mu \text{ a.s.}$ for the same values of d and z as above. “Jet” models, in which the ejecta are funneled into a small solid angle, predict angular sizes ~ 4 times smaller than corresponding spherical ones but may already be ruled out because they vastly underpredict the observed radio flux ([Rhoads 1997]).

Thus, if GRB0508 proves to be typical, it is unlikely that radio afterglows will be directly resolved by VLBI. An upper limit of $300 \mu \text{ a.s.}$ has been set by the VLBA eight days after the burst ([Taylor, Beasley, & Frail, 1997]).

Afterglows may, however, be resolved indirectly by interstellar scattering. Inhomogeneities in the density of free electrons (N_e) affect the refractive index (n) governing the propagation of radio waves through the interstellar medium: $\delta n = -(r_e \lambda^2 / 2\pi) \delta N_e$, where $r_e \equiv e^2 / m_e c^2$, and λ is the wavelength. Extensive evidence supports the conclusion that these inhomogeneities span a broad range of spatial scales (at least 10^9 to 10^{14} cm) with a power-law power spectrum

$$\Phi_{N_e}(\vec{q}) \equiv (2\pi)^{-3} \int d^3 \vec{s} \langle \delta N_e(\vec{x}) \delta N_e(\vec{x} + \vec{s}) \rangle e^{i\vec{q} \cdot \vec{s}} = C_N^2 q^{-11/3}, \quad (3)$$

where \vec{q} is the spatial wavenumber conjugate to separation \vec{s} and is measured in radians per unit length (cf. [Armstrong, Rickett, & Spangler 1995]). Small-scale atmospheric density fluctuations have power spectra of the same mathematical form, so that radio scintillation has much in common with optical seeing ([Coulman 1985]).

Scintillation modulates the flux in two conceptually different ways (cf. [Rickett 1990]):

(i) *Refractive* scintillation, the random focusing and defocusing of rays, can be understood and analyzed entirely within geometric optics. Given a turbulent spectrum such as (3), the strength of refractive scintillation varies smoothly with the angular size of the source (inhomogeneities smaller than the projected source size have no effect because surface brightness is conserved) and with wavelength ($\delta n \propto \lambda^2$). Refractive scintillation is insensitive to the observing bandwidth.

(ii) *Diffraction* scintillation is a physical-optics effect; it can be explained as the interference among multiple paths from source to receiver. Since it requires the interfering rays to be mutually coherent, diffractive scintillation is quenched when the angular size of the source or the bandwidth of observation is too

large. Diffractive scintillation leads to a Rayleigh distribution of flux, with fluctuations equal to the mean: $P(F) = \exp(-F/\langle F \rangle)$, $\langle F^2 \rangle = 2\langle F \rangle^2$.

Among common radio sources, only pulsars are compact enough to display diffractive scintillation, but refractive scintillation affects interstellar masers and extragalactic sources as well.

In §2, we consider diffractive scintillation of radio afterglows. We find that this is just possible but very sensitive to the actual angular size of the afterglow and to the radio frequency of observation. Detection of diffractive scintillation would strongly constrain the Lorentz factor of the burst. In §3, we describe the more robust predictions for refractive scintillation, which can also be used to constrain the angular size. Flux variations relative to the mean $\approx 0.1(\theta_s/\mu \text{ a.s.})^{-7/6}\nu_{10}^{-2}$ are predicted on timescales ~ 10 hr. A summary and some suggestions for observing strategies are presented in §4.

2 DIFFRACTIVE SCINTILLATION

For convenience, we imagine in this section only that the scattering medium is compressed onto a plane perpendicular to the line of sight at distance z_{sc} (“thin-screen approximation”). The characteristic deflection due to scattering is

$$\begin{aligned}\theta_d &= 2.341\lambda^{11/5}r_e^{6/5}(SM)^{3/5} \\ &= 2.93\nu_{10}^{-11/5}\left(\frac{SM}{10^{-3.5} \text{ m}^{-20/3} \text{ kpc}}\right)^{3/5} \mu \text{ a.s.}\end{aligned}\tag{4}$$

Here $SM \equiv \int C_N^2(z)dz$, where z is a coordinate along the line of sight, is called the *scattering measure*. We have scaled it by a value typical for extragalactic sources at high galactic latitudes ([Spangler et al. 1993]).

The precise definition of θ_d involves the *phase structure function*, $D_\phi(s)$, which is the mean-square phase difference accumulated along parallel lines of sight separated by transverse distance s . It follows from eq. (3) that $D_\phi(s) = (s/s_d)^{5/3}$ for an appropriately chosen constant s_d . Then $\theta_d \equiv (ks_d)^{-1}$, where $k \equiv 2\pi/\lambda$ is the wavenumber. Apart from a numerical factor, s_d is equivalent to the Fried parameter r_0 of optical seeing.

The scatter-broadened image acts somewhat as a Michelson stellar interferometer, with a characteristic spacing between the arms $a \sim z_{\text{sc}}\theta_d$. Fringes develop on the observer’s plane if the angular size of the source is smaller than the resolution of the interferometer, $\theta_a = (ka)^{-1}$. Diffractive scintillation

is caused by the motion of the observer through this fringe pattern. Therefore, diffractive scintillation is seen only if

$$\theta_s < (kz_{\text{sc}}\theta_d)^{-1} = 2.25\nu_{10}^{6/5}z_{\text{sc, kpc}}^{-1}(SM_{-3.5})^{-3/5} \mu \text{ a.s.}, \quad (5)$$

where $SM_{-3.5} \equiv SM/(10^{-3.5} \text{ m}^{-20/3} \text{ kpc})$. Condition (5) can be satisfied if the source size is close to the lower limit discussed in §1.

In order to see diffractive flux variations of relative order unity, however, it is also necessary that $D_\phi(r_F) > 1$, or equivalently that $s_d < r_F$, where $r_F \equiv \sqrt{d_{\text{scr}}/k}$ is the Fresnel length (cf. [Rickett 1990]). The rays of geometric optics have an intrinsic width $\sim r_F$, and in order to create interference effects, the phase fluctuations must be strong enough to create distinct rays. If this condition is not fulfilled, there is only *weak scintillation* (weak modulation of the flux): a good optical site is in the weak-scintillation regime, so that the stars overhead do not twinkle. The condition for strong scintillation in the present case is

$$\nu < 10.4(SM_{-3.5})^{6/17}z_{\text{scr, kpc}}^{5/17} \text{ GHz}. \quad (6)$$

At the maximum frequency allowed by eq. (6), the source-size limit becomes

$$\theta_s(\nu_{\text{max}}) < 2.35(SM_{-3.5})^{-3/17}z_{\text{scr, kpc}}^{-11/17} \mu \text{ a.s.}. \quad (7)$$

Intriguingly, this is comparable to the minimum source size estimated in §1 on physical grounds. Both the scattering measure SM and the effective distance z_{scr} scale as $\csc b$ with galactic latitude [$b(\text{GRB0508}) \approx 27^\circ$]. Hence the *maximum* measurable size (7) is $\propto (\sin b)^{14/17}$.

Future afterglows may therefore be indirectly resolvable by diffractive scintillation when they occur at moderately high latitude, especially if they can be detected shortly after the burst ($\lesssim 1 \text{ d}$). Scintillation will be quenched at some frequency below (6) because of the $\nu^{6/5}$ dependence of the constraint (5), and the transition frequency will provide an indirect measure of the source size. The scattering measure along the line of sight can be internally estimated from the scintillation timescale,

$$t_{\text{diff}} = \frac{s_d}{v_\perp} = 3.1\nu_{10}^{6/5}(SM_{-3.5})^{-3/5} \left(\frac{v_\perp}{30 \text{ km s}^{-1}} \right)^{-1} \text{ hr}. \quad (8)$$

In very strong scintillation, diffractive flux variations are uncorrelated at radio frequencies differing by more than the *decorrelation bandwidth*

$$\Delta\nu_{\text{dc}} = \frac{c}{2\pi\theta_d^2 d_{\text{scr}}} \approx 7.6\nu_{10}^{22/5}(SM_{-3.5})^{-6/5}d_{\text{scr, kpc}}^{-1} \text{ GHz}. \quad (9)$$

As this formula shows, the frequencies of interest are not far from the borderline between strong and weak scintillation, where $\Delta\nu_{\text{dc}} \sim \nu$. On the one hand, this is fortunate because the afterglows are faint and must be observed with a broad bandwidth. On the other hand, it is unfortunate because $\Delta\nu_{\text{dc}}$ measures an independent combination of SM and d_{screen} .

The angular size limit (5) and the decorrelation bandwidth (9) become more severe as the distance to the scattering screen increases, and it might therefore be supposed that scattering in the gamma-ray burst's host galaxy (if it exists) or in the intergalactic medium (IGM) would suppress diffractive scintillation. At worst, however, such scattering has the effect of replacing one incoherent source (of size θ_s) with an effective incoherent source of somewhat larger angular size $\hat{\theta}_s$. Diffractive scintillation due to the Galactic interstellar medium (ISM) will still occur provided that $\hat{\theta}_s$ satisfies the limit (5) with d_{scr} determined by the path length through the Galactic ISM. Also, a deflection angle $\hat{\theta}_d$ in the host galaxy contributes to the effective source size in proportion to

$$\frac{d_{\text{ISM}}}{d_{\text{host}}} \hat{\theta}_d \sim 10^{-6} \hat{\theta}_d.$$

Hence, scattering in the host can probably be neglected, for the same reason that orbiting satellites looking down enjoy much better seeing than ground-based telescopes looking up.

Scattering by the IGM is negligible presuming (in the absence of better information) that the scattering measure scales as the path length times the square of the mean electron density:

$$\frac{SM_{\text{IGM}}}{SM_{\text{ISM}}} \sim \frac{1 \text{ Gpc}}{1 \text{ kpc}} \left(\frac{2 \times 10^{-7} \text{ cm}^{-3}}{0.02 \text{ cm}^{-3}} \right)^2 \sim 10^{-4}.$$

We have assumed a fully-ionized IGM containing most of the baryons allowed by primordial nucleosynthesis ($\Omega_b h_{50}^2 = 0.05 \pm 0.01$: [Izotov, Thuan, & Lipovetsky 1997]) and taken the local electron density from [Taylor & Cordes 1993]. In the case of GRB0508, scattering by an intervening galaxy associated with the $z = 0.835$ absorption system might be comparable to that due to the local ISM, but there appears to be no intrinsically bright galaxy on the line of sight [[Fruchter & Bergeron 1997]], so it is likely that the absorption comes from the outer halo of a galaxy, where the electron density and scattering measure are likely to be small.

3 REFRACTIVE SCINTILLATION

Following [Coles et al. 1987] (henceforth CFRC), the normalized spatial correlation of the flux due to refractive scintillation is

$$C(\vec{s}) \equiv \frac{\langle F_\nu(\vec{x}) F_\nu(\vec{x} + \vec{s}) \rangle}{\langle F_\nu \rangle^2} - 1 = 8\pi r_e^2 \lambda^2 \int_0^\infty dz \int d^2\vec{q} e^{i\vec{q}\cdot\vec{s}} \Phi_{N_e}(q_x, q_y; q_z = 0; z) \\ \times \left| V\left(\frac{\vec{q}z}{k}\right) \right|^2 \exp \left[- \int_0^\infty d\bar{z} D'_\phi \left(\frac{\vec{q}z_{<}}{k}, \bar{z} \right) \right] \sin^2 \left(\frac{q^2 z}{2k} \right). \quad (10)$$

Here the line of sight runs from the observer at $z = 0$ to the source at (effectively) $z = \infty$. The electron-density spectrum Φ_{N_e} [eq. (3)] depends on z via the coefficient $C_N^2 \rightarrow C_N^2(z)$, which reflects changes in the strength of the turbulence along the line of sight. We take $C_N^2(z) = C_N^2(0) \exp[-(z \sin b/H)^2]$, where $C_N^2(0)$ is the local value near the Sun, and $z \sin b$ is the height above the plane. The flux correlation depends upon the average (or sum) of the phase fluctuations along the line of sight, hence the z component of \vec{q} is set to zero in eq. (10).

The quantity $V(\vec{r})$ is the visibility of the source on baseline \vec{r} , which like \vec{q} and \vec{s} in this formula, is a vector transverse to the line of sight. We assume a gaussian image brightness distribution for the source, $I_\nu(\vec{\theta}) \propto \exp(-\vec{\theta}^2/2\theta_s^2)$, so that $V(\vec{q}z/k) = \exp(-q^2 z^2 \theta_s^2/2)$.

Finally,

$$D'_\phi(\vec{r}, z) \equiv 4\pi r_e^2 \lambda^2 \int d^2\vec{q} \Phi_{N_e}(q_x, q_y; q_z = 0, z) [1 - e^{i\vec{q}\cdot\vec{s}}], \\ = 2^{4/3} \frac{3\pi^2 \Gamma(7/6)}{5 \Gamma(11/6)} C_N^2(z) r_e^2 \lambda^2 s^{5/3} \quad (11)$$

is the differential phase structure function. In other words, $D'_\phi(\vec{r}, z) dz$ is the contribution of the slab $(z, z+dz)$ to the mean-square phase difference between lines of sight separated by \vec{r} . The quantity $z_{<} \equiv \min(z, \bar{z})$.

The three final factors in equation (10) can be regarded as the squares of “visibilities” due to the intrinsic source size, to the scattering, and to Fresnel optics. The characteristic angular scales associated with these visibilities at $z = H \csc b$ are θ_s , θ_d , and the *Fresnel angle*

$$\bar{\theta}_F \equiv (kH \csc b)^{-1/2} = 2.57 \nu_{10}^{-1/2} \left(\frac{H \csc b}{\text{kpc}} \right)^{-1/2} \mu \text{ a.s.} \quad (12)$$

Actually, the Fresnel visibility at $z = H \csc b$ is

$$V_F(\vec{r}) \equiv \frac{\sin(k\theta_F r/2)}{k\theta_F r/2}, \quad (13)$$

so that $V_F(0) = 1$. All three visibilities have the effect of restricting the range of wavenumbers \vec{q} that contribute to $C(\vec{s})$. They occur multiplicatively in equation (10) because the effective source size seen by the observer is a convolution of the intrinsic surface brightness distribution $I_\nu(\vec{\theta})$ with the scatter-broadened image of a point source, and with a sort of Fresnel image.

The root-mean-square variation in the flux relative to its mean value is $\sqrt{C(0)} \equiv m_R$, the *modulation index*. From equation (10),

$$\begin{aligned} m_R &= \left[\frac{1}{4} \Gamma(7/6) \Gamma(1/3) \right]^{1/2} r_e \lambda^2 \theta_{\text{eff}}^{-7/6} C_N^2(0)^{1/2} (H \csc b)^{1/3} \\ &= 0.12 \left(\frac{\theta_{\text{eff}}}{10 \mu \text{ a.s.}} \right)^{-7/6} \nu_{10}^{-2} \left(\frac{H \csc b}{1 \text{ kpc}} \right)^{1/3} \left(\frac{C_N^2(0)}{10^{-3.5} \text{ m}^{-20/3}} \right)^{1/2}, \end{aligned} \quad (14)$$

where the effective source size is

$$\theta_{\text{eff}} \equiv \left[\theta_s^2 + (0.7064\theta_d)^2 + (0.8482\theta_F)^2 \right]^{1/2}. \quad (15)$$

This extends the results of CFRC, who gave explicit formulae for m_R in the limit of large intrinsic size, $\theta_s \gg \theta_d, \theta_F$. Our result (14) is an interpolation formula. The numerical coefficients in the definition of θ_{eff} have been chosen so that equation (14) is exact when any one of the three characteristic angles ($\theta_s, \theta_d, \theta_F$) is much larger than the other two.

Refractive scintillation occurs on the timescale required for the line of sight to cross the image at a mean distance $d_{\text{scr}} \approx H \csc b/2$,

$$t_{\text{ref}} = \frac{\theta_{\text{eff}} H \csc b}{2v_\perp} = 7.0 \left(\frac{\theta_{\text{eff}}}{10 \mu \text{ a.s.}} \right) \left(\frac{H \csc b}{\text{kpc}} \right) \left(\frac{v_\perp}{30 \text{ km s}^{-1}} \right)^{-1} \text{ hr}, \quad (16)$$

assuming that the motion of the line of sight is more rapid than the internal velocities of the medium. The full temporal correlation function is then $C(v_\perp \tau)$ at lag τ . Note that unlike t_{diff} [eq. (8)], t_{ref} remains constant or decreases with increasing frequency, depending on the intrinsic image size. At frequencies above limit (6), where the scintillation is weak, the two timescales merge into a single one: the time required for the line of sight to cross the Fresnel length.

In principle, it is possible to estimate the angular size from the amplitude and timescale of refractive scintillation at a single frequency. In practice, it

may be difficult to disentangle refractive flux variations from instrumental and atmospheric noise; furthermore, the parameters $C_N^2(0)$ and H are imperfectly known. Therefore it will be safer to measure m_R at several frequencies. Equations (14), (15), and (4) imply that $m_R \propto \nu^{-2}$ at relatively high frequencies, where $\theta_{\text{eff}} \approx \theta_s$ is frequency-independent; and that $m_R \propto \nu^{+17/30}$ at low frequencies, where $\theta_{\text{eff}} \approx \theta_d \propto \nu^{-11/5}$. Hence $m_R(\nu)$ has a peak:

$$\begin{aligned} \nu_{\text{peak}} &= 4.30 \left(\frac{\theta_s}{10 \mu \text{ a.s.}} \right)^{-5/11} (SM_{-3.5})^{3/11} \text{ GHz}, \\ m_{R, \text{ peak}} &= 0.270 \left(\frac{\theta_s}{10 \mu \text{ a.s.}} \right)^{-17/66} \left(\frac{H \text{ csc } b}{\text{kpc}} \right)^{-7/33} \left(\frac{C_N^2(0)}{10^{-3.5} \text{ m}^{-20/3}} \right)^{1/22} \end{aligned} \quad (17)$$

These formulae assume that θ_s is substantially larger than the Fresnel angle (12) at the peak.

4 Discussion

If radio afterglows of gamma-ray bursts are indeed produced by relativistic blastwaves at cosmological distances, then their small angular size and high surface brightness puts them in an extremely interesting part of parameter space with respect to interstellar scintillation. Both diffractive and refractive scintillation are possible for these sources.

Diffractive scintillation is sensitive to the radio frequency of observation, ν , and the angular size of the source, θ_s . It may have been marginally possible to have seen diffractive scintillation in GRB0508 at $\nu \approx 10$ GHz if $\theta_s \lesssim 2 \mu \text{ a.s.}$ [eq. (5)]. Future afterglows from sources at high galactic latitude will present other opportunities for observing diffractive scintillation, which will be recognized because

- the flux variations are of unit strength, $\langle F^2 \rangle = 2\langle F \rangle^2$ [but contrary to the situation with pulsars, scintillation will be correlated accross a broad frequency band, cf. eq. (9)];
- the timescale decreases with decreasing radio frequency, and is on the order of a few hours [eq. (8)];
- the effect vanishes abruptly below a frequency determined by the scattering measure and the angular size of the source [eq. (6)].

Diffractive scintillation will allow the interstellar medium to be used as a Michelson stellar interferometer to resolve angular sizes measured in micro-arcseconds, far too small for conventional VLBI.

Refractive scintillation will occur at all frequencies and for all angular sizes, though its amplitude depends algebraically on both of these parameters. The timescale will range upward from a few hours. The amplitude, though less than unity, will be large ($\sim 10\%$) unless θ_s , and hence the Lorentz factor of the blastwave, are much larger than predicted by current models [eq. (14)]. Refractive scintillation therefore can also be used to constrain θ_s and Γ_s , though it will not provide quite so sharp a test as diffractive scintillation.

Some implications for observing strategies are the following:

One wants to collect data at several frequencies, roughly in the range 2 – 20 GHz.

For diffractive scintillation, the flux should be sampled on timescales ~ 1 hr, and the first data points should be taken as early as the sensitivity of the equipment permits, since the source will be smaller and less likely to be over-resolved by the scattering [see eqs. (5) & (7)]. One should probably attempt to see diffractive scintillation in sources at high galactic latitude ($\gtrsim 30^\circ$) only, once again because these are least likely to be overresolved. Ideally one would wait for a source close to a line of sight on which the scattering parameters have been well determined from observations of extragalactic sources and globular-cluster pulsars.

For refractive scintillations, many of the same considerations apply. In this case, however, one can afford to make observations later in the lifecycle of the afterglow, at longer time intervals, and at lower galactic latitude. It will be important, however, to minimize or accurately subtract the contribution of receiver and atmospheric noise to the flux variations, since the amplitude of the modulation index is critical to the estimate of the angular size.

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